Number transcoding for First and Second Language Learners

by

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Abstract

The goal of this study was to explore the effect of language on English number transcoding by comparing the errors made by First Language Learners (FLL) with those made by Second Language Learners (SLL). Errors were analyzed through the lens of ADAPT cognitive model of transcoding. Eighty-seven students in grade 3 (i.e., 51 FLL and 36 SLL) were recruited from Ottawa schools. They attempted to write down 30 verbally-presented numbers which varied from 3 to 7-digits. Overall, the two groups showed similar transcoding performance. The errors increased with the number of digits and did not differ across groups. However, FLL made more syntactic errors whereas SLL made more lexical and combination errors. Although both groups made errors applying the transcoding procedures, some SLL were still developing their numerical lexicon. Individual differences in transcoding were related to visual-spatial and verbal working memory. The results align with ADAPT model of number transcoding.

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Reading and writing numerals is one of the fundamental skills that children acquire in mathematics, a building block for future arithmetic development, and an essential skill in life. Extensive research has explored the mechanisms and mental processes that underlie number comprehension and production (Barrouillet, Camos, Perruchet, & Seron, 2004; Gerard Deloche & Seron, 2018; Gérard Deloche & Seron, 1982; McCloskey, 1992). More specifically, *transcoding* is the process of transforming one numerical code into another. For example, when children read aloud numbers written as digits, they must convert a numerical symbol (e.g., 4) into a verbal code (e.g., /fɔ:(r)/, the number word). If they are asked to write verbally dictated numbers, they must do the opposite, converting a verbal code into a written numerical symbol. The transcoding errors that children make provide insight into children's initial understanding of multidigit numbers and they may reveal the underlying cognitive mechanisms involved in number processing. Transcoding difficulties may also be a marker for later difficulties in mathematics (Byrge, Smith, & Mix, 2014). Thus, the goal of this thesis was to explore transcoding skills for children who have not yet mastered the process, but nevertheless have some skill.

Numerical symbols are universal, but the verbal forms for numbers vary according to the spoken language. For example, in some languages the way numbers are spoken is consistent with how they are written (i.e., in Chinese, the number 12 is spoken as “ten two” which reflects the base-ten structure of the written digits). Other languages do not have a direct correspondence to the base-ten structure used in written digits. For example, number 12 in English is named “twelve” and in French is named “douze”; in

both languages the number words that represent 12 are unique words which are not transparent to the base-10 structure of the written digits. Thus, the number naming system of a particular language can help or constrain children's grasping of multi-digit numbers, based on how consistent the number names are with the base-ten structure of the written number system (Dowker, Bala, & Lloyd, 2008).

Cross-national comparisons of mathematics achievement have consistently shown a net superiority of Asian students compared to American and European students. This advantage is often attributed to social and educational factors such as the involvement of children and parents with schoolwork (Stevenson, Lee, & Stigler, 1986) or differential experiences in schooling (Geary, 2004). Research has shown that, in addition to educational and social influences, language is an important factor in mathematics learning and achievement (Klein et al., 2013; Ng & Rao, 2010).

According to Statistics Canada, in 2011 Canadians reported more than 200 different first languages, with 20% of Canadian population reporting that they speak a language other than English or French at home. Among those people who reported speaking a language other than English or French at home, 32% spoke that 'other' language exclusively (Statistics Canada, 2012). Because many Canadian children are exposed to another language before starting school, they are also presumably experiencing early numeracy in a language other than English. Depending on the transparency of their home language to the decimal system, they may be disadvantaged, or they may be in a favourable position in understanding basic number concepts such as the place value concept. Thus, the goal of this thesis was to conduct a detailed analysis of transcoding errors made by students whose first language was English (i.e., First

Language Learners) in comparison with the ones made by students whose primary language was not English (i.e., Second Language Learners), and to assess the impact of language experience on understanding multi-digit numbers.

The Arabic Number System

Although the verbal number system is language specific, the written Hindu-Arabic (hereafter ‘Arabic’) number system is trans-linguistic, which means that it can be read in any language in which the reader is familiar (Chrisomalis, 2013). The Arabic number system is the most widely used written number system today and it is used to represent numbers in many countries across the world. The Arabic number system has a set of only 10 symbols (digits from 1 to 9, and 0) which can be combined to form all numbers. The value of each digit within a number is determined by its position in the sequence: the value of each position increases in powers of 10 from right to left, which makes it a base-10 system. Zero is used as a place holder, indicating that there is no basic value to be associated with a power of 10 (e.g., in number 308, 0 indicates that there is no value associated with 10^1). The Arabic number system has been adopted universally for its simplicity and its strong computational power. However, due to incompatibility between the structure of different verbal number systems and Arabic numerals, the Arabic number system may be difficult to master, despite its simplicity.

Very early in development, children first learn about numbers through number words, by learning how to count, and then later, when they are taught the Arabic symbols, they learn to map them to the previously learned number words (Pixner et al., 2011). Children can learn the mapping between words and digits early in development without understanding the quantities involved if they learn to asemantically assign a

verbal label to a written symbol (Bialystok, 1992). Simultaneously, children progress towards understanding that each number word refers to a specific value, and eventually they master the mappings between digits and quantities (Jiménez Lira, Carver, Douglas, & LeFevre, 2017). Jimenez Lira et al. found evidence that word-digit mapping predicts individual differences in word-quantity mapping, and both of these abilities predict children's ability to map between digits and quantity. Therefore, the ability to create a correspondence between the number word and the numerical symbol is at the core of children's understanding of numerical concepts. However, the successful mastery of the place-value structure of the Arabic number system is a developmental process and shows considerable variability among individual children (Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011).

Research on Transcoding

Research on transcoding shows that children make two kinds of errors, syntactic and lexical (e.g., Power & Dal Martello, 1990; Seron, Deloche, & Noel, 1992). Lexical errors are mainly substitution of digits (e.g., “sixty-five” → “25”) which maintain the structure of the number as a whole. Syntactic errors, which are more numerous than lexical errors, are mainly additions or omissions of 0 which affect the magnitude of the number, resulting in an increase or decrease in the length of the sequence of digits (e.g., “two hundred and twenty-one” → “20021”, “five thousand fifty-four” → “554”). Similar patterns of errors have been observed in many studies of transcoding (Imbo, Bulcke, Brauwer, & Fias, 2014; Moeller et al., 2011; Pixner et al., 2011; van Loosbroek, Dirx, Hulstijn, & Janssen, 2009). Nuerk et al. (2011) provided a comprehensive review of numerous effects (i.e., verbal lexicon and the structure of the number word, directionality

of reading and writing, neurocognitive correlates) specific to multi-digit number processing which are important in understanding the general function of numerical cognition.

Transcoding performance varies with specific language characteristics, indicating that the number word structure influences children's numerical development (Imbo et al., 2014; Klein et al., 2013; Seron & Fayol, 1994). For example, place value understanding is more difficult in languages with inverted number words – that is, when 25 is named as “five-and-twenty” (i.e., German, Austrian, Flemish) and in languages with complex number word structures (i.e., French) – that is, when 80 is named as “quatre-vingt”, corresponding to “four-twenty” in English.

Pixner et al. (2011) investigated the influence of two number-word systems on transcoding within one culture. In Czech, there are two different number-word systems, one with inverted decade-unit structure (e.g., “three-and-forty” for 43), and one with non-inverted structure (e.g., “forty-three” for 43). Seven-year-old children from the Czech Republic had to perform the transcoding task in both number-word systems. The same children made more errors in the inverted number word system than in the non-inverted system, thus showing that even when controlling for cultural and educational influences, the structure of the number word system affects transcoding.

The ADAPT model was proposed by Barrouillet et al. (2004) as a cognitive model for number transcoding. In their study, Barrouillet et al. (2004) examined the transcoding errors made by normally developing 7- to 8-year-old children in grades 2 and 3. They found that syntactic errors were more frequent than the lexical errors among the younger

children, and that grade 3 children made fewer transcoding errors than grade 2 children. This developmental pattern was predicted by the ADAPT model.

Consistent with the ADAPT model, working memory skills play an important role in number transcoding. One study conducted by Camos et al. (2008) found that 7-year-old children with low working memory capacity made more transcoding errors than children with high working memory capacity, showing that working memory capacity is a constraining factor which accounts for errors in number transcoding. The impact of working memory capacity on transcoding performance was also explored by Zuber et al. (2009), who focused on transcoding skills of 7-year old children in a language with inversion. Their findings indicate that language specific attributes, such as inversion, strongly influence performance in transcoding through an increase in cognitive demands such as working memory, thus confirming the important role of working memory in number transcoding.

Byrge et al. (2014) examined 4- to 6-year-old preschoolers' transcoding skills and their understanding of place value prior to formal instructions. Children showed expanded number writing or literal transcoding (e.g., 642 → 600402), suggesting that they tried to align the spoken names with the written forms. Many syntactic errors are similar in that children represent the spoken words by mapping them directly with their corresponding digital forms, thus showing that the rules that govern the syntactic principle in forming multi-digit numbers have not been acquired yet.

In summary, transcoding errors in most studies were characterized as either lexical or syntactic. The occurrence of these errors has been explained based on different cognitive models of number transcoding, as described in the next section.

Cognitive Models of Number Transcoding

Several cognitive models have been proposed to describe the processes involved in number transcoding. These models emerged from studies with children or with adult patients with different neuropsychological conditions, and they continue to provide a solid framework for research on number transcoding. Although the different models uniformly reflect that lexical and syntactic information concerning numerals is processed separately, they diverge as to whether it is necessary to compute an intermediary semantic representation between the input and the output code (Barrouillet et al., 2004), and therefore, they can be categorized as either semantic or asemantic.

Semantic Models

According to *semantic models*, the verbal input is transformed into an internal semantic magnitude representation through a comprehension process for further cognitive processing, and then, through a production process, the semantic representation is converted into the required output format (McCloskey, 1992). One such cognitive model was proposed by McCloskey et al. (1985) who postulated that, during transcoding, the phonological sequence of the number word is converted into an internal semantic representation. The representation specifies, in abstract form and independent of the presentation code, the basic quantities (i.e., the face value of a digit) in a number and the power of ten associated with each (McCloskey, 1992). For example, according to this semantic model, the numeral “534” would be represented as $\{5\}10^2$, $\{3\}10^1$, $\{4\}10^0$. As reflected in Figure 1, this model clearly separates the mechanisms (comprehension vs. production) and their components (verbal vs. Arabic, lexical vs. syntactic) involved in number transcoding. Due to this granular dissociation, this model has been successful in

identifying the bottleneck (i.e., the internal semantic representation) in transcoding processes, however, the model has been controversial due to its assertion that all input (spoken or written, Arabic or verbal) is channeled through the same abstract semantic form for processing (Della Sala, Gentileschi, Gray, & Spinnler, 2000).

Figure 1. McCloskey's cognitive model of numeral processing and calculation

In line with McCloskey's model, Power and dal Martello (1990) proposed a similar modular semantic model of transcoding. However, according to their model, the semantic representation closely reflects the verbal word structure of the number, therefore

it is dependent on the characteristics of the input code. The semantic representation is constructed based on sum or product relationships between the primitives and by triggering different operators. The concatenation operator (noted as “&”) is invoked when primitives (symbolized as “C”) are in a product relationship. For example, “300” is represented as (C3)x(C100); the concatenation operator is invoked: “3 & 00” results in 300. The overwriting operator (noted as “#”) is activated when numbers are in a sum relationship. For example, “105” is represented as (C100)+(C5); the overwriting operator is invoked: 100#5 produces 105. This model was used to explain most of the transcoding errors made by children, through deficits in activation of the operators. For example, when a child wrote the verbally dictated number “*one hundred and four*” as “1004”, the error was explained as a deficit in activating the overwriting operator (#) because the lexical elements were in a sum relationship (the quantity “hundred” PLUS the quantity “four”). However, this model cannot explain the transcoding errors in languages that are not fully aligned with the base 10 structure reflected in the Arabic number system. For example, inversion, an attribute specific to certain languages, like German, cannot be explained just based on sum and product relationships between the number word elements using only two operators.

The semantic models represent the first attempts of researchers to explain the mechanisms and cognitive processes involved in number transcoding. Although they have been very useful in explaining some of the transcoding errors made by adults with neurological problems and also by children, the semantic models assume that transcoding relies on understanding the quantities that the verbal input represents. Other researchers

have proposed asemantic models which do not require understanding number meaning. Furthermore, these early models did not account for learning and developmental changes.

Asemantic Models

In contrast to semantic models, another type of cognitive models for transcoding numbers from verbal to Arabic form is the *asemantic model*. According to this type of cognitive model, number transcoding implies a direct translation between the numerical input and the required output by applying a set of translation rules, without passing through an intermediate semantic magnitude representation. For example, writing the number “346” does not require the person to comprehend the quantity that the number represents, that is, the sum of 3 hundreds, 4 tens, and 6 units.

Deloche and Seron (1987) proposed an asemantic model based on their analyses of the errors made by aphasic patients who were asked to transcode word numbers into the corresponding Arabic numerals, and vice versa. They emphasized the asemantic structure of their model by identifying several processes involved in transcoding numbers from verbal form to Arabic numerals. According to this model, the first step consists of *parsing* the verbal numeral to identify the primitives, followed by the *categorization* of primitives based on the class they belong to and on their position in the class, and then, through the *transcoding process*, a set of rules are activated and applied, culminating with the *production* of the Arabic numeral. By using a small number of rules, this model was able to describe the transcoding process, however, the model has some limitations. One of the limitations is that it always assumes the existence of a three-slot frame (i.e., blank spaces to be filled), irrespective of the size of the number to be transcoded. Another limitation is that the rules are consistently applied, independent of the frequency of

numbers being transcoded, and therefore, the model does not account for developmental changes and progress in number transcoding.

To address these limitations, Barrouillet and colleagues proposed the **ADAPT** model (**A Developmental Asemantic Procedural Transcoding**), which outlines the steps involved in transcoding numbers from verbal form (phonetic or written) to Arabic numeral, based on the principle that there is no need for an intermediate semantic representation of the quantity related to the verbal numeral (Barrouillet et al., 2004). As the name suggests, this is a *developmental* model of transcoding, the first of this kind, which captures the acquisition of new transcoding rules based on already acquired number knowledge that is stored in long term memory (LTM). Hence, according to ADAPT, the processing of the most frequent numbers changes from algorithmic processing (i.e., parsing the number in segments or its lexical primitives) to direct memory retrieval of their digital form, as a result of practice and repetition of new units and procedures. Therefore, the model takes into account the evolving processes in number transcoding.

The developmental assumptions in ADAPT account for language-specific differences in number systems (Zuber, Pixner, Moeller, & Nuerk, 2009). For instance, in French, some numbers that are represented as groups of primitives (i.e., “quatre-vingt” for 80) will be stored in LTM as units due to their frequent usage, a process similar to the classical process of learning through associations, in this case between the verbal units and the digital forms. ADAPT is also a *procedural* model, meaning that the process of converting from one format to another relies on a set of procedures that trigger different actions when certain conditions are met. These procedures form the production system of

the model, see Figure 2.

Figure 2. High-level schematic representation of the ADAPT model

As depicted in Figure 2, in the first step of the model, the dictated verbal numeral is temporarily stored in a *phonological buffer*. The length of the verbal numeral and the similarity between the parts of the string determine the storage difficulty of the information in the phonological buffer. For example, four-digit numbers entail more storage than three-digit numbers since they contain more number words. A *parsing* process scans the verbal string in the phonological buffer and divides it into lexical primitives, which become the units that are sent sequentially to *working memory (WM)* to be processed.

Early in development, each primitive represents a single word (e.g., one, ten, or eleven), and *long-term memory (LTM)* is accessed to determine its class (units, teens, decades). With development, some groups of primitives (e.g., twenty-four, fifty-six, ninety-eight) start to be represented in LTM as units, and therefore, the parsing of these groups of primitives stops, and they are retrieved directly from LTM. Moreover, the parsing process not only distinguishes the processing units that need to be transcoded, but also the processing units that have the role of separators, like *hundred*, *thousand*, or *million* which dictate how the units are transcribed by triggering the corresponding transcoding rules.

A sequence of digits (i.e., a *chain* in the model) is constructed in working memory (WM), based on the set of *procedures* that are activated. The procedures, which perform different actions based on certain conditions, form the core of the production system of the model. For example, the P1 procedure is triggered when the parsing process identifies one representational unit, retrieves its digital form from LTM, and places it in the *working memory store (WMS)*, a phonological type buffer for short term storage, similar to “articulatory loop” in Baddeley’s memory model (Barrouillet et al., 2004). Similarly, the procedures P2, P3, and PM process the separators (i.e., hundred, thousand, and million), by programming in WM *frames* (i.e., blank spaces) of two, three, or six slots (e.g., 1 __, 5 ____, or 3 _____), depending on the separators indicated in the number. The P4 procedure is triggered when the end of the number string is reached; it places the information from WMS in the chain of digits built in WM, and it fills the remaining slots with zeros. See Table 1 for a complete list of all the procedures in the ADAPT model.

Table 1

Transcoding procedures in ADAPT model

Procedure	Verbal Input	Conditions		Actions
		WMS	Frame	
P1	Lexic	No	No	Find digital form in LTM; place it in WMS
P2a	Hundred	No	No	Set 1 in Chain; Set Frame in Chain; (Chain = 1__)
P2b	Hundred	Yes	No	Set WMS in Chain; clear WMS; (Chain = WMS__)
P2c	Hundred	No	Yes	Set 1 left to Frame (Chain = Chain + 1__)
P2d	Hundred	Yes	Yes	Set WMS left to Frame; clear WMS;
P3a	Thousand	No	No	Set 1 in Chain; Set Frame in Chain (Chain = 1___)
P3b	Thousand	Yes	No	Set WMS in Chain; clear WMS; set Frame in Chain
P3c	Thousand	No	Yes	Fill empty slots with 0's; Set Frame ___ in Chain
P3d	Thousand	Yes	Yes	Set WMS right in frame; clear WMS
PMb	Million	Yes	No	Set WMS in chain; clear WMS; set frame _____ in chain
PMc	Million	No	Yes	Fill empty slots with 0's; Set Frame _____ in Chain
PMd	Million	Yes	Yes	Set WMS right in frame; clear WMS; fill empty slots with 0's
P4a	End	Yes	No	Set WMS in Chain (Chain = Chain + WMS)
P4b	End	No	Yes	Fill empty slots with 0's
P4c	End	Yes	Yes	Set WMS right in frame; clear WMS

Note: WMS = working memory store, a buffer for short-term storage; WMS = Yes/No reflects whether information is/isn't in the buffer. Frame = Yes/No indicates the presence/absence of empty slots in the chain of digits. Lexic = representational unit in LTM; End = end of string signaled by the parser; Procedures P2a, P2c, P3a, and P3c are not needed to process numbers in English language

In the ADAPT model, the procedures are activated when certain conditions are met. The conditions evaluate the type of input (lexical unit, separator, or end of string), assess the presence or absence of information in the working memory store, the presence or absence of a frame, and the presence of empty slots in the chain of digits that is being constructed in working memory. The declarative knowledge held in working memory represents the verbal units selected by the parser, the digital form of the verbal units retrieved from LTM, and the representations constructed by the procedures. These three types of representations constitute the three classes of conditions (i.e., presence of information from LTM, the existence of a frame, and the presence of digits in the frame) that trigger the procedures (Barrouillet et al., 2004). Depending on which condition is present, procedures perform different actions, resulting in the construction of the chain of digits in working memory which is then placed in a buffer for its written transcription. Figure 3 shows an example of the transcoding processes based on ADAPT model.

Figure 3. Transcoding steps based on ADAPT for the input ‘three thousand nine hundred thirty-seven’. The gray boxes represent information retrieved from LTM (i.e., that was available in the phonological buffer) and that activates the indicated procedure.

By comparing computational data with data from developmental studies, Barrouillet et al. (2004) showed that the model permits precise predictions of errors in number transcoding. Because ADAPT is an asemantic production system, it predicts the different types of errors that are produced as a result of the incorrect treatment of the lexical input. For example, the transcoding of three-digit numbers can lead to different errors based on the context in which they are presented. When three-digit numbers were presented in isolation, the most frequent error made by children was adding a 0 after the hundreds (i.e., “eight hundred fifteen” transcoded as “8015”), whereas when the three-digit chunks were embedded in larger numbers, the most frequent error was the deletion of 0 (i.e., “eight thousand one hundred five” transcoded as “815”). This pattern of errors supports the assumption that transcoding is based on an asemantic pathway that processes inputs sequentially rather than a semantic pathway in which transcoders understand that 2300 is the sum of 2000 and 300 (Barrouillet et al., 2004).

Because the model is procedural, it predicts that the level of difficulty in transcoding a number is based on the number of procedures involved. Also, the model is able to distinguish between lexical and syntactic errors based on the pathways taken in transcoding (i.e., algorithmic versus direct retrieval). For instance, difficulties in automatization of retrievals lead to lexical errors. In contrast, difficulties during algorithmic processes produce syntactic errors. Thus, the ADAPT model is able to predict not only the number of transcoding errors based on the number of invoked procedures, but it can also predict the types of errors that children make in transcoding based on the types of rules that are required in the model.

Unlike other transcoding models that focus mainly on rules and procedures

involved in transcoding, ADAPT also includes domain-general cognitive processes such as working memory and storage (Zuber et al., 2009). Although Barrouillet et al. (2004) developed the ADAPT model based on the French number language, they claimed that the model is applicable in any language. The main difference across languages is the number and the type of procedures that are called during the transcoding process. Moreover, the model can account for transcoding errors in languages with specific characteristics (i.e., inversion), as well as in languages that are transparent to base-10 system with just some minor changes in procedures (Barrouillet et al., 2004).

Influence of language on number knowledge

Language is one source of individual differences in children's early numeracy skills (Cankaya, LeFevre, & Dunbar, 2014). Children's linguistic skills predict their mathematical performance on early numeracy measures that involve knowledge of the symbolic number system (e.g., naming or writing the Arabic digits), presumably because learning the rules of the number system is similar to mastering any symbolic representational system (Jiménez Lira et al., 2017). LeFevre et al. (2010) identified three independent pathways in the development of mathematical skills: linguistic (e.g., knowledge of number names), quantitative (e.g., knowledge of how many), and attentional (e.g., working memory, spatial attention). LeFevre et al. (2010) found that the linguistic pathway was the only pathway implicated in all of the mathematical outcomes, suggesting that these skills are central to mathematical learning. The interdependence between language and mathematical cognition was also emphasized by Dowker and Nuerk (2016) who identified several linguistic levels that influence numerical cognition: conceptual and phonological properties of a language, the grammatical structure of a

language, the semantic meaning and the lexical composition of the number words, as well as the phonological and orthographic properties of a language, thus showing that linguistic influences on number processing are ubiquitous (Dowker & Nuerk, 2016).

Present Study

The goal of the present study was to explore the role of language and the effect of the complexity of number-word structure on children's transcoding skills. As part of a larger project, grade 3 children were asked to write Arabic numbers in response to verbally-presented English stimuli. All of these children were learning mathematics in English but for some of the children, English was their first language, whereas for others, English was their second language. I explored the effect of language experience on children's transcoding performance by analyzing the transcoding errors of the two groups of children.

I hypothesized that the Second Language Learners would make more transcoding errors than the First Language Learners because they had less experience with the English number word structure. More specifically, I hypothesized that the Second Language Learners would have a smaller English number lexicon than First Language Learners and thus make more lexical errors. Furthermore, the Second Language Learners would rely more on algorithmic processes for transcoding numbers than on direct retrieval from long term memory. Hence, I also hypothesized that the Second Language Learners would make more syntactic errors than the First Language Learners, since syntactic errors are linked to difficulties in algorithmic processes.

I also hypothesized that individual differences in working memory would influence the efficiency in transcoding complex numbers that require more procedures.

More specifically, because the Arabic number notation system depends on the relative location of digits, I hypothesized that visual-spatial memory would be correlated with the number of syntactic errors. I expected that children with low visual-spatial WM would have difficulties in applying the procedures that place the digits in the correct positions.

Another goal of the study was to analyze the number and the type of transcoding errors that children make, based on the ADAPT cognitive model, and to test whether the model predicted those errors. According to ADAPT, the number of transcoding errors can be predicted by the number of procedures required to transcode a given number. In order to test this prediction, I determined the structure of each of the presented stimuli and the number of procedures involved in transcoding each of the stimuli, see Appendix B.

In summary, in this thesis, I examined whether there is a difference in transcoding performance between children whose primary language is English and children who speak English as a second language, and I analyzed the transcoding errors through the lens of the ADAPT cognitive model of number transcoding.

Method

The LLAMA (Language Learning and Math Achievement) project is a large, international project which focuses on the role of language in mathematics learning. Children in the study come from a variety of language contexts including French or Irish immersion environments, as well as English Language Learners from Ottawa and Montreal. As part of this project, children completed various types of measures, which included general cognitive measures (Spatial Span, Black White Stroop, Digit Forward/Backward, Matrix Reasoning), linguistic measures (WIAT, PPVT, RAN Digit), basic symbolic math measures (Order Judgment, Number Comparison/Ordering), math

and linguistic measures (Transcoding, Math Vocabulary, Symbol Decision Task), and math outcomes (Number Line Estimation, Arithmetic Fluency, Key Math Problem Solving/Algebra). For this study, I used the transcoding data collected as part of the LLAMA project in Ottawa in 2019 to examine children's ability to map between English number words and Arabic digits, and to compare the transcoding performance of First Language Learners with Second Language Learners.

Participants

The present study has received clearance from Carleton University Research Ethics Board-B (CUREB) and from Ottawa-Carleton Research and Evaluation Advisory Committee (OCREAC). Permission to conduct testing was also obtained from the schools' principals. Consent forms were provided to parents/guardians of each child. Participation was completely voluntary. Eighty-seven students (*Mean* age = 104 months, *SD* = 3 months, range from 8:1 to 9:2 years:months; 51% girls) in grade 3, were recruited from Ottawa elementary schools. All children spoke English fluently. However, 51 students spoke English as their first language and 36 students spoke another language as their first language (i.e., Chinese, Arabic, Hindi, Russian, Turkish, Spanish, Gujarati, Dutch, Japanese, Tigrinya, Hebrew, Urdu, Malayalam, Cantonese, Raknine, Somali, or Cambodian). Of the 81 mothers who provided information about their highest level of education, 2.5% had less than high school, 4.9% had a high-school diploma, 24.7% had a college degree, 39.5% had a university degree, and 28.4% had a post-graduate degree. The level of education that mothers received did not differ across the two language groups (English as a first language vs. English as a second language) $t(79) = 1.07, p > .05$.

Materials and Procedures

Transcoding. In the transcoding task, the students were verbally presented a number, and they were asked to write it down in Arabic digits. The numbers were pre-recorded by a native English speaker. For each trial, the experimenter played the pre-recorded audio file of the number word to the student; if the student had trouble writing down the digit version of the number, the experimenter asked the student if he/she wanted to hear the number one more time. If the student said yes, then the experimenter played the audio file one more time.

Before the actual test, the students had two practice trials in order to familiarize themselves with the procedure. The practice trials consisted of two easy two-digit numbers (45 and 36). The test consisted of a maximum of 30 experimental trials: Six trials for each digit lengths three to seven (see Table 2). The numbers in each digit set were selected such as they covered different levels of complexity (i.e., numbers containing non-zero digits, numbers containing the digit zero in the middle or at the end, numbers containing different structures like decades, decade-unit, unit-hundred-unit; see Appendix B for all covered number structures). Since the same stimuli were used for testing students in French immersion programs as well as students in Montreal whose first language is French, the language requirement of the French number naming was manipulated such that the last two digits for half of the numbers involve complex decade structures such as 70, 80, or 90. The numbers with these structures did not increase the level of difficulty for students in the English program given the structure of the English number system. Trials were presented in a fixed order, starting with 3-digit numbers and ending with 7-digit numbers. Testing continued as long as the student successfully wrote

down at least one number correctly in any given set (e.g., writing down at least one number correctly for the 4-digit numbers). The testing stopped when all of the trials for a given digit length were incorrectly written (i.e., all of the 5-digit trials were incorrect). Each student was allowed to take up to 30 seconds to write down the digit. If the student spent too much time writing a number, the experimenter encouraged the student to try for the next number and proceeded to the next trial. Each trial transcribed correctly was scored as 1, such as the minimum score for all the trials was 0 and the maximum was 30. The reliability analysis based on the 30 items showed a Cronbach's alpha of .89.

Table 2

Stimuli used in the transcoding task

3-digit	4-digit	5-digit	6-digit	7-digit
101	1 545	42 000	246 000	6 002 000
392	2 398	16 070	581 000	4 000 070
210	4 063	14 030	603 100	1 400 000
688	3 072	82 067	400 678	5 080 000
834	5 302	20 137	574 321	3 000 000
976	6 183	93 284	297 783	2 090 080

Working Memory Tasks. Students completed three working memory measures: spatial span task, digit forward and digit backward tasks.

Spatial span task. This task measured students' visual-spatial working memory using an iPad application called PathSpan (Hume & Hume, 2014). In the PathSpan application, students saw 9 green circles on the screen. On each trial, a given number of

circles (span) lit up in a fixed pattern. The students watched and followed the pattern closely, and then, reproduced the pattern by pressing the circles in the same order as they had been shown. There was one practice trial of 2 circles which was demonstrated by the experimenter. There were 3 trials for each span. Span-length started with a 2-circle sequence, increasing by one if at least one sequence was copied correctly, up to a maximum of 21 trials (i.e., sequence lengths of 3, 4, 5, 6, 7, 8, and 9). Testing discontinued when the participant got all three trials in a span length incorrect. Scoring for this task was the total number of correct trials.

Figure 4. PathSpan iPad application used in Spatial Span task

Digit forward and Digit backward task. Digit forward is an index of children's verbal short-term memory (i.e., phonological loop), whereas digit backward provides information about children's verbal working memory. In these tasks, students listened to numbers which the experimenter presented by playing an audio file on an iPad application, and then they had to repeat the numbers in the same order (digit forward), or in reverse order (digit backwards). There were three practice trials of 2-digit spans (1

practice trial for digit forward and 2 practice trials for digit backward). There were two trials for each span ranging from 3-digit span to an 8-digit span. If the student got both trials incorrectly for a given span, testing was discontinued.

Table 3

Stimuli used in digit forward task

Item	Span 1	Score	Span 2	Score
		(0/1)		(0/1)
1.	2-9		4-6	
2.	3-8-6		6-1-2	
3.	3-4-1-7		6-1-5-8	
4.	8-4-2-3-9		5-2-1-8-6	
5.	3-8-9-1-7-4		7-9-6-4-8-3	
6.	5-1-7-4-2-3-8		9-8-5-2-1-6-3	
7.	1-8-4-5-9-7-6-3		2-9-7-6-3-1-5-4	
8.	5-3-8-7-1-2-4-6-9		4-2-6-9-1-7-8-3-5	

Table 4

Stimuli used in digit backward task

Item	Span 1	Score	Span 2	Score
		(0/1)		(0/1)
1.	2-1		1-3	
2.	3-5		6-4	
3.	5-7-4		2-5-9	

4.	7-2-9-6	8-4-9-3
5.	4-1-3-5-7	9-7-8-5-2
6.	1-6-5-2-9-8	3-6-7-1-9-4
7.	8-5-9-2-3-4-6	4-5-7-9-2-8-1
8.	6-9-1-7-3-2-5-8	3-1-7-9-5-4-8-2

Results

The results are presented in five sections. The first section contains descriptive information about the results for the overall frequencies and percentages of errors per number set and language group. The second section displays the types of errors per number set and language group. Analyses of the relation between the transcoding errors and ADAPT model are presented in the third section. The fourth section presents the results related to the relation between working memory and transcoding performance, and the last section contains the results of a logistic mixed-model analysis of transcoding performance. When the assumption of homogeneity of variance was violated, the Greenhouse-Geisser corrected degrees of freedom were reported.

Transcoding

Frequency of responses. Responses on each trial were categorized as correct, errors, or nonresponses. A nonresponse occurred when the student did not provide an answer, or the student made six errors in a row and testing was discontinued. Students made a total of 871 errors (33.4%, $SD = 4.7$) and 410 nonresponses (15.7%, $SD = 5.9$) on the 2610 transcoding trials. Table 5 shows the number and percentage of errors and nonresponses for each of the number sets (i.e., 3- to 7-digits; 522 possible responses per set). The number of errors and of nonresponses increased with the number of digits. In the 7-digit set, the number of nonresponses exceeded the number of errors, reflecting the difficulty of the items with 6 or 7 digits.

Table 5

Number and percentage of errors and non-responses by number set

Number Set	Errors			Nonresponses		
	<i>n</i>	%	<i>SD</i>	<i>n</i>	%	<i>SD</i>
3-digit	33	3.79	1.12	0	0	0
4-digit	122	14.01	1.88	6	1.46	0.64
5-digit	212	24.34	2.19	44	10.73	1.65
6-digit	311	35.71	2.31	106	25.85	2.31
7-digit	193	22.16	2.59	254	61.95	2.98

Note. There were six trials in each number set.

Frequency of errors per language group and number set. Overall, the First Language Learners produced 518 errors (33.9% of their responses, $SD = 4.91$) and the Second Language Learners produced 353 errors (32.7% of their responses, $SD = 4.55$). There was no difference in the number of errors across groups for the number sets, as shown in Table 6.

Table 6

Transcoding performance (percentage of errors) for each language group per digit set

Number Set	Second Language (<i>N</i> = 36)			First Language (<i>N</i> = 51)		
	<i>n</i>	%	<i>SD</i>	<i>n</i>	%	<i>SD</i>
3-digit	13	6.02	1.07	20	6.54	1.17
4-digit	49	22.69	1.88	73	24.33	1.43
5-digit	72	36.36	2.01	140	50.00	2.75
6-digit	144	77.84	2.33	167	72.29	3.27
7-digit	75	73.53	2.49	118	71.08	2.68

Note. There were six trials in each number set and thus 216 and 306 possible responses for each set for the Second- and First-Language groups, respectively. The percentage error is based on number of attempts (i.e., excluding non-responses).

Analysis of percentage correct answers. The percentage of correct answers was analyzed in a 2 (language group: First Language Learners vs. Second Language Learners) x 5 (number set: 3-digit vs. 4-digit vs. 5-digit vs. 6-digit vs. 7-digit) mixed ANOVA. The means are shown in Figure 5. There were four outliers which had studentized residual values less than -3.00. Analyses were run with and without the outliers. Both resulted in same statistically significant results and similar confidence intervals; therefore, the outliers were not removed. The percentage of correct responses varied with number set, $F(3.41, 289.72) = 204.72, p < .001$, partial $\eta^2 = .707$. Post hoc analysis with a Bonferroni adjustment revealed that students' transcoding performance significantly decreased from 3-digit to 4-digit numbers ($M_{\text{difference}} = 1.08$), 95% CI [.55, 1.61], $p < .0001$, from 4-digit

to 5-digit numbers ($M_{\text{difference}} = 1.42$), 95% CI [.87, 1.97], $p < .0001$, and from 5-digit to 6-digit numbers ($M_{\text{difference}} = 1.93$), 95% CI [1.35, 2.50], $p < .0001$, but not from 6-digit to 7-digit numbers ($M_{\text{difference}} = .35$, 95% CI [-.11, .82], $p = .317$). The main effect of language group showed that there was no statistically significant difference in mean transcoding performance between language groups $F(1, 85) = .212$, $p = .646$, partial $\eta^2 = .002$. Also, there was no statistically significant interaction between the number of digits and language group on correct transcoding performance, $F(3.41, 289.72) = 1.69$, $p = .162$, partial $\eta^2 = .020$.

Figure 5. Mean Correct Responses for each language group by digit number set

To summarize, both language groups had similar overall transcoding performance. The percentage of correct responses decreased as the number of digits increased, with both groups having the best performance on the 3-digit set and the worst performance on the 6- and 7-digit number sets.

Classification of error types. The errors were classified as lexical errors, syntactic errors, or a combination of both. Each trial was classified as to whether it included one or more lexical and one or more syntactic errors. Thus, students may have made more than a single error of either type per trial. Lexical errors were mainly substitution of digits, maintaining the length of the digit chain (e.g., 844 instead of 834). Syntactic errors occurred when digits were omitted or added to the sequence, thus affecting the overall magnitude of the number (e.g. 150045 instead of 1545). The errors that included at least one lexical and one syntactic error were categorized as combination errors (e.g. 2127 instead of 20137). Children made one or more syntactic errors on 678 trials, they made lexical errors on 85 trials, and they made combination errors on 91. Seventeen trials contained errors which could not be classified into any of the three categories, and therefore, they were removed from analysis. The types of errors were analyzed further within each category.

Syntactic errors. The syntactic errors were subdivided into eight different subcategories: additive composition error, when the added 0's matched or partially matched the place value of the preceding digit (e.g., 2398 → 2000398 or 2398 → 200398), multiplicative composition error, when a 1 followed by 0's acted as an intruder (e.g., 688 → 61088), omission of 0 (e.g., 3072 → 372), or omission of digits other than 0 (93284 → 9384), addition of digits by perservation (2398 → 23398), or random addition of digits (93284 → 932854), partial processing (82067 → 82060), and inversion (5032 → 5023). As shown in Figure 6, most of the trials that were classified as pure syntactic errors were due to either omission of 0, or to additive composition errors. Finally, 21% of the total number of syntactic errors were a mixture of two or three pure

syntactic errors. These errors were given a distinct error code, but they were included in the syntactic category. See Appendix A for all mixed syntactic errors.

Figure 6. Percentage of pure syntactic errors by categories of errors.

Lexical errors. Three subcategories were identified within the lexical error category: substitution of primitives (e.g., 1545 → 1546), class substitution error (e.g., 16070 → 6070), and intrusion errors, in which they wrote part of the number as a word (e.g., 5 080 000 → 5 *million* 80 000). There were no trials on which students made multiple types of lexical errors in transcoding a given number. As shown in Figure 7, most of the pure lexical errors were due to substitution of primitives. Only one student made intrusion errors. Intrusion errors are not common in children, but they have been reported in studies of transcoding in Alzheimer patients (Della Sala et al., 2000).

Figure 7. Percentage of lexical error subcategories out of lexical errors

Combination errors. As shown in Table 7, combination errors were mainly combinations of a substitution error (lexical) and an additive composition or omission of zero (syntactic).

Table 7

Number and types of combination errors with examples

Combination Errors	Number → Response	n
Substitution + Additive	574321 → 500,74,00,874	33
Substitution + Omission of 0	3072 → 3,77	16
Substitution + Inversion	2398 → 2958	10
Substitution + Additive + Omission	297783 → 2097093	9
Substitution + Omission	1545 → 146	8
Substitution + Additive + Omission of 0	603100 → 50031	7
Substitution + Omission + Multiplicative	297783 → 2971097	3
Substitution + Omission of 0 + Inversion	246000 → 263	2
Substitution + Omission + Additive + Multiplicative	297783 → 2009710083	2
Substitution + Omission of 0 + Omission	400678 → 4038	1

Errors by number sets. The types of errors made for each of the number sets are shown in Table 8. In general, students made more errors for the 4, 5, and 6-digit sets than for the 3- and 7-digit sets in all error categories. There was a 10% decrease in the number of lexical errors from the 5-digit to the 6-digit number set, showing that, as the number of digits increases, the students had more difficulties with the application of procedures rather than with memory retrievals.

Table 8

Total number of errors and percentages by category for each number set

Number set	Lexical		Syntactic		Combination	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
3-digit	9	28.13	22	68.75	1	3.13
4-digit	17	13.93	92	75.41	13	10.66
5-digit	33	15.79	150	71.77	26	12.44
6-digit	18	6.02	239	79.93	42	14.05
7-digit	8	4.17	175	91.15	9	4.69

Errors by language groups. Figure 8 displays the percentage of errors for the three main error categories for each language group. A chi-square test of homogeneity was run, with an adequate sample size established according to Cochran (1954). The distribution of errors varied with language group, $\chi^2(2) = 11.19, p = .004$. First Language Learners made relatively more syntactic errors than the Second Language Learners (83.1% vs 73.9%). In contrast, First Language Learners made relatively fewer lexical errors than the Second Language Learners (8.6% vs. 11.9%). First Language Learners also made relatively fewer combination errors than the Second Language Learners (8.3% vs. 14.2%). According to the ADAPT model, lexical errors occur when transcoding is based on a direct retrieval from LTM. The difference in the distribution of lexical errors across groups suggests that Second Language Learners have less automated memory retrieval.

Figure 8. Percentage of errors for each error category as a function of language group

Because syntactic errors were the most frequent, the frequency across groups of the syntactic error subcategories were analyzed in more detail. The most frequent syntactic errors for both groups were omission of 0 and additive composition errors but the relative frequency of these types of errors was different across groups. The First Language Learners produced more omissions of zero (35.3%) than the Second Language Learners (18.5%). The First Language Learners produced the highest number of omission of zero errors for the stimulus “fourteen thousand thirty” (i.e., 14030). The first zero in the sequence was omitted most of the times, resulting in the faulty response of “1430”. The last zero was omitted only once. Although the last zero is part of the lexical primitive “30” which is retrieved from LTM, the first zero is not associated with any primitive and it requires the application of rules to fill the empty slot. According to ADAPT, the

omission of zero errors were produced as a result of the faulty application of transcoding procedures.

In contrast, the Second Language Learners made more additive composition errors (26.4%) than the First Language Learners (16.6%). According to Barrouillet et al. (2004), when students make additive composition errors (i.e., literal transcriptions) in transcoding, no rules are invoked to process the separators, but instead, their digital representation is retrieved from LTM (e.g., two hundred and ten $\rightarrow$ 20010). The fact that the additive composition errors were more common in Second Language Learners indicates that the Second Language Learners had not mastered the transcoding rules as well as the First Language Learners, thus showing a difference in transcoding levels between the two language groups.

In order to confirm the independence between the two types of errors (i.e., lexical versus syntactic), a correlation analysis was run between the number of lexical and syntactic errors that children made, on average, on each of the 30 numbers. The correlation was not significant, $r(28) = -.153, p = .420$, supporting the view that the two types of errors are influenced by different factors.

To summarize, the two language groups had similar overall transcoding performance: Correct responses decreased as the number of digits in the number increased. However, the frequency of types of errors differed across groups: The First Language Learners made more syntactic errors, suggesting that they encountered difficulties in applying the production rules, whereas the Second Language Learners made more lexical errors and more combined (lexical + syntactic) errors, suggesting that they were less able to directly retrieve primitives from LTM.

ADAPT Rules and Errors

According to the ADAPT model, the difficulty in transcoding a given number depends on the number of processing steps required for its transcoding. The number of ADAPT rules needed to transcode all the dictated numbers was evaluated, as shown in Appendix B. The correlation between the number of ADAPT rules and the average number of errors observed for each number was $r(28) = .51, p = .004$, supporting the ADAPT model assumption that the number of processing steps in transcoding predicts the number of errors. A scatterplot of this correlation is presented in Figure 9. In general, there is a moderately close relation between the number of ADAPT procedures required, based on the model predictions, and the number of errors that students made. However, there is also considerable variability in error frequency within the ADAPT rule counts across the 30 stimuli.

Figure 9. Correlation between ADAPT procedures and average number of errors per number

As shown in Figure 9, the number of errors made on stimuli that required three procedures was higher than expected. There were two numbers which, according to ADAPT, required only three procedures in transcoding: 42000 and 3000000. Interestingly, an equal number of errors (i.e., 28 errors) was made on these two stimuli (and thus only one dot is shown in Figure 9). This number of errors is relatively high compared to the number of errors produced when more procedures (i.e., four procedures) were required in transcoding. Note that both these numbers end in many zeros, which is why only three ADAPT procedures were required. Consistent with the ADAPT model, students had difficulty processing the separators (i.e., thousand and million) or with the application of the P4 procedures (i.e., those which control the end of string operations by

emptying the contents of working memory storage). For example, the most common error for both 42000 and 3000000 was the omission of a zero which resulted in faulty transcriptions of these numbers (i.e., 4200 or 30000).

A similar observation was made for the two stimuli (i.e., 574 321 and 297 783) which required the highest number of procedures in transcoding (i.e., 8 procedures). Note that these two numbers do not have any zeros. These two numbers also produced an equal number of errors (i.e., 45 errors), which is reflected by one dot in Figure 9. The most common type of error observed in transcoding these two numbers was an additive composition error (e.g., 500704321 or 20097000783). The number of errors that students made in transcoding these numbers is relatively low compared to the number of errors produced for numbers with a lower number of procedures (i.e., 7 procedures). The difference is that the numbers that required fewer procedures in transcoding contained zeros (i.e., 603100, 246000, 581000), thus showing that the presence of digit zero makes it harder for students to transcode a given number irrespective of the number of invoked procedures. Therefore, the number of ADAPT procedures was only one of several predictors of transcoding difficulty for these children, which explains the moderate correlation between the number of procedures and the number of errors in transcoding.

One other characteristic of the ADAPT model is that it accounts for learning. As number structures like decades (i.e., seventy) or decade-unit structures (i.e., forty-five) are more frequent, new representational units are formed in LTM, and the transcoding process moves from an algorithmic process to a direct retrieval from LTM. Consistent with this view, students in the present study made very few errors transcoding decade (0.3 %) or decade-unit structures (2.0 %), indicating that by the third grade, most students

can retrieve these structures directly from LTM instead of transcoding them algorithmically. See Appendices C and D for more details about the errors made on decade and decade-unit structures.

According to Barrouillet et al. (2004), transcoding of hundreds produced different errors in 4-digit numbers compared to 3-digit numbers. Consistent with this hypothesis, students transcoding five or six-digit numbers with the sub-structure *UHU* (*Unit-Hundred-Unit*), as in *UTUHU* (*Unit-Thousand-Unit-Hundred-Unit*) or *UHUTUH* (e.g., 5302, 603100) made errors that were not observed on numbers with the *UHU* structure in isolation (i.e., 3-digit numbers). For three-digit numbers, the main type of error was an additive composition error (i.e., $101 \rightarrow 1001$). However, when the *UHU* structure was embedded in a 5 or 6-digit number (i.e., 5302 or 603100), students frequently omitted the zero in the *UHU* part (i.e., $5302 \rightarrow 532$; $603100 \rightarrow 63100$). The difference in error types for the same number sub-structure shows that distinct processes are invoked when transcoding these structures when they are part of a longer verbal string versus when they are in isolation. This finding is consistent with the assumption that transcoding is asemantic, that is, it does not depend on the meaning of the number (i.e., the quantity it represents), but instead on the state of the system when a particular numerical structure is transcribed (Barrouillet et al., 2004). In conclusion, ADAPT did provide a good explanation for children's transcoding errors, accounting for asemantic aspect of transcoding.

Individual Differences in Working Memory and Transcoding

The third objective of this study was to see whether students' working memory skills were related to their transcoding performance. The intercorrelations between the

memory tasks and the transcoding error rate as well as the means and standard deviations for all WM measures are reported in Table 9. Only spatial span was significantly correlated with the average number of errors students made on the 30 stimuli.

Table 9

Intercorrelations among WM tasks and total number of errors per child

Variable	Number of Errors	Digit Backward	Digit Forward	Spatial Span
Digit Backward	-.193			
Digit Forward	-.082	.429**		
Spatial Span	-.319**	.307**	.138	
<i>Mean</i>	10.01	4.16	7.32	10.79
<i>SD</i>	4.74	1.68	1.93	3.15
<i>Minimum</i>	1	2	2	1
<i>Maximum</i>	21	9	14	18

Note. $N = 87$

These data were analyzed using multiple regression to predict transcoding performance from scores on tasks that tap into working memory components (i.e., Digit Backward task which taps into the verbal and Central Executive component of WM, Digit Forward task which reflects the verbal short term memory, and Spatial Span task which is related to visual-spatial WM). The model was significant, $F(3, 81) = 3.407$, $p = .021$, $R^2 = .11$, adj. $R^2 = .08$. As shown in Table 10, only Spatial Span was a significant unique predictor of performance accounting for 7.4% of variance in transcoding

performance. Thus, the higher a student scored on Spatial Span task, the fewer transcoding errors he or she produced.

Table 10

Summary of Multiple Regression Analysis predicting transcoding performance from WM components

Variable	B	SE_B	β	p	Unique R^2
Digit Backward	-.302	.341	-.107	.379	.038
Digit Forward	.009	.285	.004	.974	.001
Spatial Span	-.432*	.166	-.287*	.011	.074*

Note. * $p < .05$; B = Unstandardized regression coefficient; SE_B = Standard error of the coefficient; β = Standardized coefficient

These results are consistent with previous findings (Camos, 2008) in which WM was correlated with transcoding performance. However, unlike findings in previous studies which showed that the Central Executive component of WM reliably predicted transcoding rates (Moeller et al., 2011), in this multiple regression analysis we found that only the visual spatial component was a unique predictor of transcoding errors. It is possible that there was some collinearity between forward and backward digit span in this analysis. The next section provides a more detailed analysis of the relation between WM components and transcoding.

Logistic Mixed Model Analysis of Transcoding Performance

In order to further investigate the differences in transcoding, I analyzed the performance on each trial for which a child attempted to write a number (1 = correct; 0 = error) using a logistic mixed-effects model which incorporates the hierarchical structure

of the data. The proposed 2-level model helps predict the outcome of a dichotomous variable in terms of log odds (i.e., logit - the natural log of the odds of an event occurring, in this case a correct response) as a linear association between different independent variables (fixed effects) and one or more random variables (random effects). The variables used at each level of analysis are shown in Table 11. The nonresponses have been removed from the analysis. A logistic mixed-effect model which contained the participants and the items as random effects was fit to the data in a stepwise forward selection procedure in order to predict the probability of correctly transcoding a number. The stepwise forward selection procedure begins with an empty model (i.e., an intercept model, without any predictors), and then the predictors are added one at a time. Level 1 predictors (i.e. the number of digits and the number of ADAPT procedures) were added first, followed by the level two predictors (i.e., the working memory measures and language); the model is then tested at each step by comparing the AIC (Akaike Information Criterion, an estimator used for model selection) values (i.e., a decrease in AIC value means that the predictor improved the model fit), and by carrying out a likelihood ratio test between the last model and the previous one using the anova function; the process stops when the model no longer improves (Baayen, Davidson, & Bates, 2008; Schweinberger, 2019).

Table 11

2-level mixed model proposed for logistic mixed model analysis

Levels of data	Factor Type	Variables
Level 2	Random factor	Participant ID
	Between participant factors	Participants' Language Status (first vs. second)
		Working Memory measures:
		digit backward total score
Level 1		digit forward total score
		spatial span total score
	Random factor	The items (the presented stimuli)
	Within participant factors	Number of digits (3, 4, 5, 6, or 7)
		Nr. of P1 ADAPT procedures (1, 2, 3, or 4)
		Nr. of P2 ADAPT procedures (0, 1, or 2)
		Nr. of P3 ADAPT procedures (0 or 1)
		Nr. of P4 ADAPT procedures (0, 1, or 2)
		Nr. of PM ADAPT procedures (0 or 1)
	Dependent variable	Transcoding score (1 = correct, 0 = incorrect)

The final minimal adequate model (see Table 12) was significantly better than an intercept-only baseline model, $\chi^2(7) = 123.59, p < .0001$.

Table 12

Mixed effects logistic for transcoding score (0 - Incorrect, 1 - Correct)

Parameter	Estimate	SE	z-value	p-value
Intercept	10.31***	0.68	15.25	< .0001
Number of Digits	-1.82***	0.13	-13.93	< .0001
P1 (LTM retrieval)	-0.18	0.13	-1.32	.187
P3 (Hundred)	-0.67*	0.30	-2.22	.026
PM (Million)	0.89*	0.40	2.23	.026
Digit Backwards	0.28*	0.14	1.99	.046
Digit Forwards	0.28*	0.13	2.20	.028
Spatial Span	0.17*	0.07	2.39	.017
Language Group	-0.35	0.43	-0.81	.419

Note. * $p < .05$, *** $p < .0001$

The odds-ratio was calculated to determine the relative odds of transcoding correctly considering the factors entered in the model, see Figure 10.

Figure 10. The relative odds of transcoding correctly for each significant predictor in the mixed-effects model

As shown in Figure 10, the transcoding performance at Level 1 was predicted by the number of digits and by the number of P3 and PM ADAPT procedures. Specifically, for each additional digit in an item, the odds of transcoding correctly were 0.16 times lower. Also, the odds of transcoding correctly were 0.51 times lower when the P3 procedure was invoked for processing the thousand operator. Interestingly, when the PM procedure was required in transcoding, the odds of transcoding correctly was 2.44 higher. The PM procedure is responsible for managing the million separator; thus, it is invoked only when transcoding 7-digit numbers. As mentioned before, students were stopped

when all of the trials for a given digit length were incorrectly written. Therefore, students who managed to transcode correctly numbers in the 6-digit number set were also more likely to attempt and be correct for items in the 7-digit set. The 7-digit numbers were relatively easier than the 6-digit numbers. This pattern of responses was also reflected in the strong correlation between the 6-digit total correct scores and 7-digit total correct scores, $r(85) = .620, p < .001$.

At Level 2, all working memory scores predicted performance, such that the odds of transcoding correctly were 1.32 times higher for students with higher digit forward scores, 1.33 times higher for students with higher digit backward scores, and 1.18 times higher for students with higher spatial span scores. None of the interactions between the independent variables were significant, however. Thus, as also predicted by ADAPT, working memory components are a significant predictor of transcoding, playing an important role in the algorithmic transcoding when students need to manipulate the procedures in order to produce the chain of digits.

Discussion

The goals of this study were to (a) determine the impact of language experience on number transcoding by comparing the transcoding errors made by the First Language Learners with those made by the Second Language Learners, (b) analyze the transcoding errors and the ability to predict them based on ADAPT, an asemantic cognitive model, and (c) investigate the influence of different working memory components on individual differences in number transcoding.

Role of language in number transcoding

Previous research suggests that children's transcoding performance is influenced by language skill. I hypothesized that Second Language Learners would make more transcoding errors than the First Language Learners because I assumed that the former group had less exposure to the English number words prior to starting school. The current results show, however, that the overall number of transcoding errors was similar between the two language groups. Thus, in the third grade, the Second Language Learners matched the overall level of transcoding performance of the First Language Learners. It is possible that an effect might be seen for younger students.

Syntactic error types were predominant for both language groups. In contrast with my hypothesis, the First Language Learners made more syntactic errors than the Second Language Learners who made more lexical and more combination errors. This pattern of errors reflects that the Second Language Learners tried to retrieve from memory the corresponding digital forms of a given number, but the retrieval failed because the information was not fully accessible. According to Barrouillet et al. (2004), the retrieval is probabilistic, and the strength of associations stored in LTM becomes weaker with less frequent experience with specific forms. It is possible that, due to their reduced experience with the English number words, the Second Language Learners had weaker associations in LTM between the verbal units and their corresponding digital forms for numbers lower than 100, thus explaining their difficulties with direct retrievals. In contrast, because the First Language Learners had more experience with English number words, they produced fewer lexical errors than the Second Language Learners.

Syntactic errors were the most common type of error for both language groups, showing that students in grade 3 have not fully mastered algorithmic transcoding for

these numbers. Within the syntactic category, the First Language Learners made relatively more omissions of 0 than the Second Language Learners. In the base 10 system, zero acts as a place holder. A zero is written when there is no value associated with a given power of ten and there is no corresponding verbal form.

In previous neuropsychological studies, it has been shown that transcoding numbers containing zero was more difficult than transcoding numbers without zeroes (Benavides-Varela et al., 2016; Granà, Lochy, Girelli, Seron, & Semenza, 2003). According to Granà et al. (2003), the digit zero can have a syntactic role (i.e., in the number 5302, zero is a null quantity associated with 10^1) or a lexical role (i.e., in number 210, zero is part of the lexical primitive 10). They reported that their patients had more difficulties transcoding a syntactic zero than a lexical zero. Similarly, in the present study, the omissions of zero produced by the First Language Learners were mainly omissions of syntactic zeros, showing that they had difficulties in applying the procedures, especially the P4b procedure that fills in the empty slots at the end of the verbal string. In contrast, the Second Language Learners made fewer omissions of zero than the First Language Learners, but they made more literal transcription errors (i.e., 976 → 900706), showing that they have not fully acquired the transcoding rules. They also made more lexical errors which suggests they are still building their numerical lexicon.

In conclusion, although I did not find a direct role of language in number transcoding, the different types of errors produced by the two groups show that there are differences in their numerical lexicons as well as in the acquisition level of the transcoding rules, revealing a subtle influence of language on number transcoding. Overall, these differences in errors suggest that the Second Language Learners were less

knowledgeable about the English number system, but that the First Language Learners made more errors applying the rules.

The Predictions of the ADAPT Model of Number Transcoding

ADAPT is an asemantic, procedural cognitive model which describes the transcoding task as a sequence of steps triggering a set of procedural rules that parse and process the verbal string, producing a chain of digits as the output. The model was developed and tested on the transcoding errors of French-speaking children. In the current study, I applied the ADAPT model to transcoding data of English-speaking children who were learning math in either their first or their second language. Overall, the model performed well in accounting for the pattern of errors. In particular, several findings supported the predictions of the model.

First, the number of procedures predicted for each item by the model accounted for about 25% of the variability in the number of transcoding errors across items, thus providing a partial account of students' transcoding performance. Second, ADAPT predicted specific types of errors for certain numerical structures (e.g., UHU) based on the length of the digit chain in which they occurred, suggesting that the transcoding process was dependent only on the current state of the processing system and not on the overall structure of the numbers. However, in this study, we had only one UHU structure in isolation (i.e., 101) and therefore, we cannot confirm that we have fully tested the asemantic nature of the transcoding process. Third, students made few errors on decade structures (i.e., twenty, seventy) or decade-unit structures (i.e., forty-one, seventy-eight), showing that these structures were being treated as lexical primitives by the transcoding system, that is, retrieved directly from LTM instead of transcribed algorithmically. This

finding is consistent with the learning aspect of the ADAPT model in that the frequent algorithmic transcoding of these structures increases the probability that they will be stored in memory and become representational units. Thus, their transcoding is no more difficult than transcoding of other lexical primitives.

Similarly, the mixed model analysis of the data, which took into consideration the participants and the stimuli as random effects, supported some of the predictions of the ADAPT model. The finding that P3 ADAPT procedure was a significant predictor of transcoding performance for the grade three students shows that students have not fully acquired the rules of transcoding and that they are still learning the rules that process the thousand separator. The fact that PM ADAPT procedure was also a significant predictor shows that once students acquired the P3 rules for processing the thousand separator, they could also master the PM rules which process the million separator, the structure of the two procedures being very similar, and the only difference being the size of the frame.

In summary, this study confirmed several predictions of the ADAPT model, specifically, those linked to the procedural and asemantic aspects of the model. The number of invoked procedures in transcoding a given number accounted for most of students' transcoding errors, however, the number of procedures were not always the best predictor for the number of errors. There were other factors that impacted transcoding performance such as the presence of the digit zero which increased the numerical complexity in a number, thus making it more difficult for children to transcode that particular number. The study also confirmed the asemantic aspect of the model by showing that the same numerical structure (i.e., Unit-Hundred-Unit) is transcoded differently depending on the state of the system and not on the quantity that particular

structure represents. Last, the learning aspect of the ADAPT model was also confirmed by showing that frequently transcoded structures become representational units that are stored in LTM and they are retrieved automatically.

Relation between Working Memory and Transcoding

Another aim of this study was to examine how working memory influences performance in transcoding. This study replicated previous findings (Camos, 2008; Moeller et al., 2011; Zuber et al., 2009) by showing that, in general, working memory is linked to transcoding performance. In the overall multiple regression analysis, only spatial span (i.e., the visual-spatial component of working memory) significantly predicted the transcoding error rates. In a place value system, the spatial position of each digit determines its value and thus, spatial position is crucial in the mastery of the transcoding task. This finding was consistent with my original hypothesis that visual-spatial memory would be correlated with the number of syntactic errors, since I expected that children with low visual-spatial memory capacity would have difficulties in applying the procedures that place the digits in the correct positions.

In contrast, in the multi-level model analysis, all three working memory components predicted performance, reflecting the high cognitive demands of maintaining information in phonological buffer while implementing the rules and constructing the chain of digits. One crucial advantage of mixed logistic models is their greater power to detect true effects (Jaeger, 2008). Thus, in comparison with the multiple regression analysis, the multi-level model analysis was more able to capture subtle effects of working memory.

In conclusion, the results provide further information about how individual differences in working memory are related to number transcoding. The results align with ADAPT model which highlights that individual differences in working memory capacity could influence the retrieval process and the storage of intermediate lexical units (Camos, 2008).

Limitations

There are several limitations in the present study. I did not have information about how much exposure to the English language children had prior to starting school. The Second Language Learners could have been exposed to mathematical concepts in English prior to starting school, in a formal (i.e., preschool, kindergarten) or informal environment (i.e., at home, speaking English with parents or siblings). Also, because the home languages spoken by the Second Language Learners were diverse, it was impossible in the current study to link the specific language spoken at home to transcoding performance. Number words in some languages (e.g., Chinese and other Asian languages) are more consistent with the Arabic system than languages which are not structured along the constraints of the Arabic base 10 system (e.g., French, Basque). Chinese-speaking children thus have some advantages in learning number words in Chinese, however, whether that transfers to a second language is unknown.

Conclusions and Implications for Future Research

In this study I examined the influence of language experience on number transcoding by comparing the skills of First Language Learners with those of Second Language Learners. By third grade, there was no significant difference in the overall number of transcoding errors between the two language groups. Syntactic errors were the

most common errors made by students in both language groups. A common transcoding mistake at this stage is the violation of syntactic rules which govern the formation of multidigit numbers. Language was related to the relative proportion of errors: Second Language Learners made relatively more lexical errors than First Language Learners, suggesting that they had less-developed numerical lexicons for English number words. Thus, the type of errors produced by the two language groups indicate that there is a subtle influence of language experience on number transcoding. These results confirm previous findings which show that language influences number transcoding in children who have already mastered numbers to 100 (Van Rinsveld & Schiltz, 2016).

The current study supports the procedural and asemantic nature of the ADAPT model and it also confirms the relation between working memory and number transcoding. Transcoding errors were related to the visual-spatial component of WM in both regression and multi-level analysis. Therefore, individual differences in number transcoding may arise from the ability to understand the spatial property of the decimal system. This finding has a possible implication for teaching multi-digit numbers. Presenting students with a chart showing the positions of the digits in a number may help them visualize the frame where the chain of digits is being built in the working memory, thus minimizing the individual differences related to the visual spatial component of working memory in the transcoding task. One neuroimaging study (Benavides-Varela et al., 2016) highlights the role of the right hemisphere in transcoding multi-digit numbers containing zeros. The authors emphasize the importance of the visual-spatial processes in the representation of digit zero in the phonological buffer, thus, providing more evidence that the ability to master the spatial relations between the digits in a number is one

relevant factor in transcoding. Therefore, educators should be aware that a place value chart may be a valuable tool in teaching place value concepts, see Figure 11. To make it more attractive, developing an interactive place value chart application for children to practice writing multi-digit numbers will help them understand the place value property of the Arabic number system in a fun and interesting way.

PLACE VALUE CHART

The number **3 043 120** can be entered in the place value chart as follows:

Millions	Hundred Thousands	Ten Thousands	Thousands	Hundreds	Tens	Ones
3	0	4	3	1	2	0

Figure 11. Sample Place Value Chart

ADAPT predicts that the difficulty in transcoding a given number is determined by the number of processing steps. The results of this study provided evidence for this claim. However, the number of transcoding rules was only a moderate predictor of transcoding performance, showing that other factors influence students' transcoding performance. Independent of the number of processing steps, students encountered difficulties in transcoding numbers that contained the digit zero. In most languages the digit zero does not have a correspondence in the verbal code. The place value chart (Figure 11) could help students to understand the role of 0 in multi-digit numbers.

The ADAPT model accounted for learning, showing that as new units are stored in LTM, the transcoding process moves from algorithmic transcriptions to direct retrievals (Barrouillet et al., 2004). These results were supported by the results of the

current study by the small number of errors that children produced in transcoding basic number structures (i.e., decades and decade-units), reflecting automatic retrieval of these structures from LTM. These results have an implication for education. Educators should be aware of the important role of working memory capacity in number transcoding, and that one possible way to decrease the load on working memory when students are learning multi-digit numbers is to orient them towards automatic retrieval in order to build a solid numerical lexicon and reduce algorithmic transcoding. The automation of transcoding of small numbers will also facilitate the transcoding of large numbers, thus increasing students' overall efficiency of transcoding.

Understanding multi-digit numbers is an important foundation for developing future mathematical skills. The transcoding task is a good way of assessing children's basic numerical skills and identifying children with mathematics difficulties. Many researchers have studied children's transcoding skills, but the selection criteria for the transcoding stimuli were very different across studies. Standardizing the design of the transcoding task, for example, to ensure that the items cover all levels of difficulty, would be a useful step. The selected stimuli should take into account the role of cognitive functions in number transcoding (i.e., working memory), language specificities in a number word system (i.e., inversion, complex decade structures), the length of the digit chain, the presence and the location of the digit zero in the digit chain, as well as the number of procedures invoked in transcoding which reflect the syntactic complexity of a number. Moura et al. (2015) suggest designing an automatic algorithm for generating the transcoding task items based on ADAPT which provides a solid base for generating items at all difficulty levels. Standardizing the transcoding task would allow more robust

assessment of children's transcoding skills and make it easier to compare the results of different studies. Thus, a standard transcoding task can be used not only for research, but also in schools. Teachers could use the task to identify students with possible future mathematical difficulties and make sure that the appropriate interventions are applied in time.

Appendix A

Mixed Syntactic Error Types

Types of Mixed Syntactic Errors

Additive + Inversion

Additive + Multiplicative

Additive + Partial Processing

Additive + Adding by perseveration

Additive + Adding by perserveration + Partial Processing

Additive + Omission of zero

Additive + Omission

Omission of zero + Inversion

Omission of zero + Multiplicative

Omission of zero + Adding digits randomly

Omission of zero + Adding digits by perserveration

Omission of zero + Multiplicative + Partial Processing

Omission of zero + Omission

Omission + Multiplicative

Omission + Additive + Multiplicative

Multiplicative + Partial Processing

Appendix B

Stimuli, their structure and the corresponding number of ADAPT procedures

Verbal numeral	Structure	Arabic Number	ADAPT PROCEDURES					
			P	P	P	P	PM	Total
			1	2	3	4		
one hundred and one	UHU	101	2	1	0	2	0	5
three hundred and ninety-two	UHDU	392	2	1	0	1	0	4
two hundred and ten	UHD	210	2	1	0	1	0	4
six hundred and eighty-eight	UHDU	688	2	1	0	1	0	4
eight hundred and thirty-four	UHDU	834	2	1	0	1	0	4
nine hundred and seventy-six	UHDU	976	2	1	0	1	0	4
one thousand five hundred and forty-five	UTUH DU	1545	3	1	1	1	0	6
two thousand three hundred and ninety-eight	UTUH DU	2398	3	1	1	1	0	6
four thousand and sixty-three	UTDU	4063	2	0	1	2	0	5
three thousand and seventy-two	UTDU	3072	2	0	1	2	0	5

five thousand three hundred and two	UTUHU	5302	3	1	1	2	0	7
six thousand one hundred and eighty-three	UTUHDU	6183	3	1	1	1	0	6
forty-two thousand	DUT	42000	1	0	1	1	0	3
sixteen thousand and seventy	PTD	16070	2	0	1	2	0	5
fourteen thousand and thirty	PTD	14030	2	0	1	2	0	5
eighty-two thousand and sixty-seven	DUTDU	82067	2	0	1	2	0	5
twenty thousand one hundred and thirty-seven	DTUHDU	20137	3	1	1	1	0	6
ninety-three thousand two hundred and eighty-four	DUTUHDU	93284	3	1	1	1	0	6
two hundred and forty-six thousand	UHDUT	246000	2	1	1	1	0	5
five hundred and eighty-one thousand	UHDUT	581000	2	1	1	1	0	5
six hundred and three thousand one hundred	UHUTUH	603100	3	2	1	1	0	7
four hundred thousand six hundred and seventy-eight	UHTUHDU	400678	3	1	1	1	0	6
five hundred and seventy-four thousand three hundred and twenty-one	UHDUTUHDU	574321	4	2	1	1	0	8

two hundred and ninety-seven thousand seven hundred and eighty-three	UHDUTUHDU	297783	4	2	1	1	0	8
six million two thousand	UMUT	6002000	2	0	1	1	1	5
four million seventy	UMD	4000070	2	0	0	2	1	5
one million four hundred thousand	UMUHT	1400000	2	1	1	0	1	5
five million eighty thousand	UMDT	5080000	2	0	1	1	1	5
three million	UM	3000000	1	0	0	1	1	3
two million ninety thousand and eighty	UMDTD	2090080	3	0	1	2	1	7

Note: U = unit; P = particular; D = decade; H = hundred; M = thousand. P1 rules are responsible for retrievals from long-term memory, P2 rules are responsible for managing hundreds (H), P3 rules are responsible for managing thousands (M), PM rules are responsible for managing millions, and P4 rules are stop rules.

Appendix C

Stimuli containing *DU* structures and their associated errors

Stimulus	DU Error
392	-
688	-
834	84, 44
976	74, 78
1545	35, 46
2398	38
4063	64
3072	75, 76, 77
6183	-
42000	-
82067	37, 77
82067	-
20137	47, 27, 87
93284	92, 32
93284	34
246000	42
581000	-
400678	38, 48, 68
574321	28, 41
574321	75, 78, 31
297783	-
297783	-

Appendix D

Stimuli containing *D* structures and their associated errors

Stimulus	Decade error
<i>210</i>	-
160 <i>70</i>	73
140 <i>30</i>	-
<i>20</i> 137	27
<i>4000070</i>	-
508 <i>0000</i>	-
209 <i>0080</i>	-

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